AUTODYN 2D PREDICTIONS FOR SMALL SCALE HP MAGAZINE CELL WALL TESTS

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BACKGROUND

Concept

The Naval Civil Engineering Laboratory is developing a new magazine concept that will reduce the land area encumbered by ESQD arcs and improve the efficiency of weapons handling operations. This new High Performance Magazine (HP Magazine) can reduce encumbered land by 80% and significantly reduce operational costs. The most important factor in the improved performance of the HP Magazine is the reduction of the Maximum Credible Event (MCE) to the Net Explosive Weight (NEW) of High Explosive (HE) in an individual storage cell. Internal cell walls are being developed to mitigate the effects of an explosion in any cell and prevent sympathetic detonation in adjacent cells. The performance of the HP Magazine is also enhanced by soil cover and tunnel type exits that reduce the safe distance for debris and overpressure. The MCE in a magazine storing conventional palletized weapons (e.g. bombs, projectiles, mines) would be reduced from about 200,000 lbs to about 10,000 lbs. The MCE for missile storage would be reduced from 100,000 lbs to 10,000 lbs. The preliminary HP Magazine concept and its key components are shown in Figure 1.

Benefits

Current magazine technology limits the net explosives load to about 350 lbs per acre of encumbered land. The HP magazine could increase this to 3000 lbs per acre allowing up to an eight fold reduction in encumbered land. The following table summarizes the savings in encumbered land with an HP Magazine.

ENCUMBERED LAND
STANDARD VS HP MAGAZINE

STORAGE (lbs)	STANDARD MAGAZINE ESQD ARC (ft)	AREA (acres)	HP MAGAZINE ESQD ARC (ft)	AREA (acres)	REDUCED AREA (%)
200,000 (Conv.)	2680	518	1000	72	86
100,000 (Missiles)	1625	190	750	40	79

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1992**	2. REPORT TYPE	3. DATES COVERED **00-00-1992 to 00-00-1992**

4. TITLE AND SUBTITLE **AUTODYN 2D Predictions for Small Scale HP Magazine Cell Wall Tests**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Civil Engineering Laboratory,Structures Division,Port Hueneme,CA,93041**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA260984, Volume I. Minutes of the Twenty-Fifth Explosives Safety Seminar Held in Anaheim, CA on 18-20 August 1992.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**30**	

Development Program

Major elements of the current development program are the characterization of the hazard, and the development of mitigation methods. The internal cell wall is a major component in the prevention of sympathetic detonation within the magazine.

In the past, testing has been required to obtain verification and acceptance of designs to prevent sympathetic detonation. Application of the results were also limited to the test configuration. It would be impossible to test all possible HP Magazine configurations and ordnance storage layouts. Therefore, development and verification of prediction models is critical to the success of the program. NCEL has been developing state of the art finite element and hydrocode models (primarily DYNA3D and AUTODYN) to predict the wall and acceptor response.

Scope of Paper

This paper presents the small scale wall development test program and the analytical techniques used to predict the wall and acceptor response. Limited test data is compared to predictions.

CELL WALL SMALL SCALE DEVELOPMENT TEST PROGRAM

Test Objectives

The objectives of these small scale tests are:

(a) to obtain data to verify and improve the analytical models which predict donor loads, wall response, acceptor loads, and acceptor response.

(b) to show the effects of specific wall design variables on the acceptor loads.

(c) to determine the wall response and acceptor loads in a $1/3^{rd}$ scale model wall test.

Scope of Test Program

Eight small scale tests are being conducted in two phases at the Naval Air Warfare Center (NAWC), China Lake. Test variables include wall mass, wall core material, wall cover material, and acceptor orientation. The configurations for Phases I & 2, Tests 1 to 8, are shown in Table 1. Figure 2 shows a typical test setup.

The tests are designed to determine the effects of design parameters on acceptor loads and response. The wall core materials (water, sand, and steel grit), wall cover materials (aluminum honeycombs and a low density

chemically bonded ceramic from CEMCOM Corp.), and acceptor orientation (parallel and perpendicular to the wall) are variables. The side by side parallel orientation of acceptors will also measure loads from acceptor impact on an adjacent acceptor.

Tests 1 through 6 are not true scale models of the prototype wall but were designed to show the relative effects of the different core and cover materials, to verify the prediction modeling, and to develop instrumentation capabilities under a less severe environment than would be obtained with a true scale model test. Tests 7 and 8 are 1/3rd scale model tests of the critical HP Magazine cell sidewall for Mk82 bomb storage.

Test Setup

The Naval Air Warfare Center (Code 3269), China Lake, CA, is constructing the test setup and conducting the tests. Typical test setup dimensions are shown in Figure 2. Details of the planned test setups can be obtained from the test plan (NCEL TM 51-92-01: Small-Scale HP Magazine Cell Wall Development Test Plan by Kevin Hager and James Tancreto, June 1992). The final test report will detail the actual test setups and conditions.

Cell Walls. Table 1 shows the wall dimensions and materials. Plywood containers are being used to hold the wall core (water, sand, steel grit). Many walls use energy absorbing cover materials opposite the acceptor. The cover materials include crushable aluminum honeycombs with 800 and 1450 psi static crushing strengths, and a CEMCOM Corp. high void ratio, light weight, chemically bonded ceramic (SA/CBC GC2).

Explosive Donor. One and two Mk 82 bombs are used as donors. All donors are oriented parallel to the test walls with their center of gravity at 2 feet above the floor slab. A single Mk82 donor will be centered between the two test walls in parameter Tests 1 through 6. Tests 7 and 8 will use two side by side Mk 82 donors to achieve 1/3rd scale model loads. The nominal explosive weight for a MK 82 is 200 lbs.

Inert Acceptors. Two instrumented inert M107-155m projectile acceptors are located opposite each test wall.

Data Acquisition

The acceptor response is being measured with self-contained accelerometers provided, installed, and operated by the U.S. Army Waterways Experiment Station (WES), Explosives Effects Division. WES is analyzing the accelerometer data and is providing acceleration, velocity, and displacement time histories. Passive structural response gages are being used to indirectly obtain the wall loadings on square and cylindrical shapes. High speed camera data will be used to obtain acceptor trajectory (initial angle and velocity of acceptors) information.

DEVELOPMENT TEST LOADS AND RESPONSE PREDICTIONS

Analysis of the small-scale cell wall test setup included two-dimensional load predictions on the cell wall, one-dimensional wall and acceptor response, and two-dimensional wall and acceptor response. The "hydrocode" AUTODYN 2D (Century Dynamics Corp.) was used for these analyses. One-dimensional models were used to provide a timely prediction of parameter effects for use in early test planning. The two dimensional model computations, which take considerably more computer time, are being conducted to obtain better response predictions. Model variables include wall mass, wall materials, energy absorbing wall cover materials, acceptor orientation, and donor charge weight.

The calculations were limited by the lack of proven equations of state (EOS) for the wall materials. Tests are planned to obtain equations of state for the steel grit, sand, and CBC materials used in the tests. Because of the current uncertainties in the equations of state, we are limiting the discussion of these preliminary analyses to wall models with sand cores. These models used an existing sand EOS and estimated EOS's for cover materials. Typical results are shown and discussed. Predictions for all models that have been run are shown in Table 2. Predictions will improve as better equations of state are developed.

Wall Loads

The pressure time-history on the donor side of the test wall was calculated using a two-dimensional Euler grid. The two-dimensional calculations provided wall loads as a function of height. Prototype full scale wall loads were determined for the dense (high load) storage of MK 82 bombs. Scale model test configurations were then analyzed and compared to the desired full scale loading. Small "scaled" distances between the MK 82 donor and the cell wall are necessary to obtain the desired scale model loads and wall velocities.

A typical two-dimensional model is shown in Figure 3. Symmetry is used to model a test with two Mk 82 donors. One Mk82 donor is modeled as a cylinder of TNT parallel to the wall. A reflecting boundary on the vertical line of symmetry gives the solution to a test setup that includes a mirror image of the model shown in Figure 3 (i.e two Mk 82 bombs and two walls). The pressure time-histories on the donor side of the wall are shown at a few selected wall heights in Figure 4. The impulses at the same points are shown in Figure 5.

Wall Response

Figures 6 & 7 show the response of the sand wall in Figure 3. Figure 6 shows the wall as it impacts the acceptor. Horizontal wall velocities varied from 390 m/s (bottom) to 116 m/s (top). Figure 7 shows the sand flow around the acceptor 1.1 ms after first impact.

One-Dimensional Acceptor Response

The one-dimensional analysis provided a timely and generally conservative prediction of acceptor loads, accelerations and velocities. Results were used to show relative effects of variables on acceptor response. The rigid body accelerations were also used to size and calibrate the accelerometers placed within the 155mm projectile acceptors.

The test wall, energy absorbing cover materials, and acceptors were modeled with LaGrange finite-difference grids. Impact-slide elements on the grid boundaries calculated contact forces between the grids. The acceptors were modeled as solid steel cylinders with the same weight and outside diameter as the inert 155mm projectiles used in the tests. Predicted response is shown in Table 2.

<u>Typical</u> <u>Model</u> <u>Results</u>. Typical analysis results are shown in Figures 8 to 12. Figure 8 shows the model for a 36" sand wall with and without a 10" thick 800 psi honeycomb cover. Figures 9 and 10 compare the pressure loads for the two models. The energy absorbing honeycomb cover significantly reduces the acceptor pressure load (Figure 8) and increases the load duration.

Figures 11 and 12 show the velocity time-histories of the acceptors and walls for the two models. Acceptor accelerations can be obtained from the slopes of the velocity-time curves. The sand wall without honeycomb cover produces an acceptor acceleration of 1.8kg (see Figure 11). The acceptor acceleration is reduced to 0.28 kg with the addition of the aluminum honeycomb.

The energy absorbing cover significantly reduces peak pressure and acceleration loads while the final velocity of the acceptor is not significantly affected.

Two-Dimensional Acceptor Response

Two-dimensional analysis used the same material models and boundary conditions, and LaGrange grids as the one-dimensional model. The two dimensional model allows wall material flow around the acceptor and accounts for the additional loads from the presented area of the 800 psi honeycomb (which is greater than the acceptor area). Predicted response is shown in Table 2.

<u>Typical</u> <u>Model</u> <u>Results</u>. Typical analysis results are shown in Figures 13 to 20. Figures 13 to 16 show material locations and acceptor velocities for a single Mk 82 donor and a 36" sand wall, with and without an 800 psi honeycomb cover. The material locations are shown at times when the acceptor velocities are approaching their maximum. Figures 13 and 15 show the sand flow around the acceptor. Although the honeycomb reduces the acceleration on the acceptor it presents a larger area to the sand flow and produces higher loads and velocity for the acceptor (compare Figures 14 and 16). Likewise, the 2-D model with honeycomb predicts higher acceptor velocities than the 1-D model.

Two-dimensional model results of the 1/3 rd scale 12" sand wall, loaded by 2 Mk 82 donors, are shown in Figures 17 and 18. The velocity of the 12" sand wall is about 200 m/s on impact with the acceptor. Figure 17 shows the wall at about 2.8 ms after impact with the acceptor. The acceptor velocity is shown in Figure 18. The peak velocity of the acceptor is about 27 m/s.

TEST RESULTS VS. PREDICTIONS

Limited preliminary test results are now available. Table 3 compares preliminary test results to predictions for 36" sand walls, with and without cover materials, and with loads from one donor (about 200 lbs of high explosive). The wall velocities generated in the sand wall tests were about 50 m/s. Table 4 compares preliminary test results and predictions for steel grit walls, with and without cover materials, and with loads from two donors (about 400 lbs of high explosive). The wall velocities generated in the tests of 8" steel grit walls were about 100 m/s.

Parallel Acceptors

<u>Sand Wall without Cover</u>. Data for Acceptor 1, parallel and 6" from a 36" sand wall, is shown in the first two lines of Table 3. Acceptor 1 is located between the sand wall and Acceptor 2 (see Figure 2). The first line of data shows the effect of the sand wall impact on Acceptor 1. Measured accelerations and velocities were bounded by the 1D and 2D AUTODYN predictions.

The second line of data shows the response of Acceptor 1 from impact with Acceptor 2. Predicted peak accelerations were high because of the simple elastic model used for the acceptors (plastic deformation, which would have reduced the peak accelerations, was not accounted for in the analytical model). The maximum velocity was close to that predicted by the 2D model.

<u>Steel Grit Wall with Cover</u>. Table 4 (lines 1 to 3) shows the measured and calculated acceptor response in a test setup with two donors and an 8" steel grit wall with 12" CBC cover (between the steel grit and the acceptor). Acceptor velocities were slightly less than the conservative 1D model predictions. The measured acceleration on acceptor 1, from impact of the CBC/steel grit wall, was about 50% higher than predicted. As expected, measured accelerations from collision of Acceptor 1 with Acceptor 2 were significantly less than predicted because of the use of a solid elastic material in the acceptor model.

Perpendicular Acceptors

<u>Sand Wall without Cover</u>. The response of acceptors perpendicular to a sand wall, without energy absorbing cover materials, is shown in line 3 of Table 3. The peak acceleration was about one half the predicted value. The peak velocity was about 2/3^{rds} the predicted velocity.

Sand Wall with Cover. Measured peak acceptor accelerations, when energy absorbing covers were used on the wall (lines 4 and 5 in Table 3), were close to predictions. The aluminum honeycomb reduced the peak accelerations on the acceptor (vs. a sand wall without a cover). With 1 donor (wall velocities around 50 m/s) the CBC material (with a static crushing strength of 2,000 psi) actually increased the peak acceleration of the acceptor. Measured velocities were less than the 2D predictions but higher than the 1D predictions. The 2D predictions are higher than the 1D predictions because they account for the increased loading area of the cover material (compare Figures 8 and 15).

Steel Grit Wall without Cover. Table 4 (line 4) shows the response of an acceptor perpendicular to an 8" steel grit wall without a cover material. The measured and predicted accelerations compared well, considering that an assumed steel grit EOS was used in the analytical model. The measured velocity, however, was 50% higher than predicted. This shows the need for development of a better steel grit EOS for use in future calculations.

Steel Grit Wall with Cover. Table 4 (lines 5 and 6) shows the response of acceptors behind an 8" steel grit wall with energy absorbing cover materials. The use of cover materials significantly reduced the measured acceptor accelerations (by a factor of 10) and velocities (by a factor of 2.5). At the wall velocities in these tests, the CBC was more effective than the aluminum honeycomb.

PRELIMINARY FINDINGS

These findings are based on first generation AUTODYN models. Better models are being developed to improve predictions. Test results are from first look data obtained in tests conducted this month. Final conclusions may differ from these preliminary findings.

- Because 1D analytical models restrict vertical flow, they generally predicted higher velocities and accelerations than 2D models.

- Variations in 1D and 2D model predictions for acceleration, in walls without energy absorbing covers, were greater with increased wall velocity.

- Wall energy absorbing cover materials with higher crushing strength produce higher acceptor accelerations. This effect diminished with increasing wall impact velocity.

- Good correlation was generally obtained between predicted and measured acceptor velocities. When large differences occurred, they could be attributed to an assumed EOS. Measured and calculated acceptor accelerations, in many cases, show large differences. This is attributable to inaccuracies in modeling and to the interpretation of calculations and measurements (e.g. peak acceleration vs. average change in velocity over critical time step).

- Test results from a 200 lb HE donor load on 36" sand walls (wall velocity = 50 m/s) show lower impact accelerations on the acceptor from the sand wall than predicted. The mitigating effect of energy absorbing aluminum honeycomb was less than expected (relative to sand wall without honeycomb). The stronger and more brittle CBC cover material did not mitigate wall impact loads at these low sand wall velocities (less than 50 m/s).

- Test results from a 400 lb HE donor load on 8" steel grit walls show that the aluminum honeycomb and the CBC are very effective at reducing acceptor accelerations at higher wall velocities (100 m/s). Preliminary results also show a reduction in acceptor velocities (vs. steel grit wall without cover materials).

- More accurate analytical modeling (planned for FY93) is needed to obtain better correlation with measurements.

Table 1. HPM SMALL SCALE WALL DEVELOPMENT TEST SCHEDULE

	#	DONOR	WALL				ACCEPTORS	
			ID	T(in)	CORE	SKIN(a)	#	ORIENT(b)
PHSE I	1	1Mk82	I	36	WATER	---	1,2	//
			II	36	SAND	---	1,2	//
	2	1Mk82	I	36	SAND	800HC	1	//
			II	36	SAND	---	1,2	//
	3	1Mk82	I	36	SAND	800HC	1	+
			I	36	SAND	---	2	+
			II	36	SAND	---	1,2	//
	4	1Mk82	I	36	SAND	1450HC	1	+
			I	36	SAND	---	2	+
			II	36	SAND	---	1,2	+
PASE II	5	1Mk82	I	36	WATER	800HC	1	+
			I	36	WATER	---	2	+
			II	36	SAND	800HC	1	+
			II	36	SAND	CBC	2	+
	6	1Mk82	I	12	STEEL(c)	---	1,2	+
			II	36	SAND	1450HC	1	+
			II	36	SAND	---	2	+
	7	2Mk82	I	8	STEEL(c)	CBC	1	+
			I	8	STEEL(c)	---	2	+
			II	8	STEEL(c)	CBC	1,2	//
	8	2Mk82	I	8	STEEL(c)	CBC	1	+
			I	8	STEEL(c)	---	2	+
			II	12	SAND	CBC	1	+
			II	12	SAND	---	2	+

(a) 800HC = 10" of Aluminum Honeycomb with 800 psi crush strength
1450HC = 10" of Aluminum Honeycomb with 1450 psi crush strength
CBC = 12" CEMCOM Corp. Chemically Bonded Ceramic (SA/CBC GC2)

(b) + = 155 mm Projectile perpendicular to wall
// = 155 mm Projectile parallel to wall

(c) Steel grit: SAE size = S170

Table 2. Small Scale HPM Wall Development Test
Acceptor Response Predictions

TEST #	DONOR (lbs)	WALL T (in)	WALL Core	COVER T (in)	COVER Cover	ACCEPTOR #	ACCEPTOR ORIENT (a)	ACCELERATION(kg) 1D Model	ACCELERATION(kg) 2D Model	VELOCITY(ms) 1D Model	VELOCITY(ms) 2D Model
1	200	36	Water	--	----	1	//	4.1		51	
						1(b)		-88		15	
		36	Water	--	----	2	//	90		46	
1,2,3	200	36	Sand	--	----	1	//	4.1	0.25	32	17.8
						1(b)		-51	-16	18.8	10.2
3	200	36	Sand	--	----	1	+	1.81	1.5	17.1	16
				10	800 H/C	2	+	0.28	0.5	15.1	24.3
4	200	36	Sand	10	1450 H/C	1	+	0.43		15	
5	200	36	Water	10	800 H/C	1	+				
		36	Water	--	----	2	+				
		36	Sand	10	800 H/C	1	+	0.28	0.5	15.1	24.3
		36	Sand	12	CEMCOM	2	+	1		16.2	
6	200	12	Steel	--	----	1	+	7.1		18	
		12	Steel	--	----	2	+	7.1		18	
		36	Sand	10	1450 H/C	1	+	0.43		15	
		36	Sand	--	----	2	+	1.81	0.3	17.1	16
7	400	8	Steel	12	CBC	1	+	1.31		27	
		8	Steel	--	----	2	+	27		37	
		8	Steel	12	CBC	1	//	3.75		54	
						1(b)		-86		32	
		8	Steel	12	CBC	2	//	89		46	
8	400	8	Steel	12	CBC	1	+	1.31		27	
		8	Steel	--	----	2	+	27		37	
		12	Sand	12	CBC	1	+	1.74	1.2	30	33
		12	Sand	--	----	2	+	22	7.7	39.3	28

(a) + = Acceptor located perpendicular to wall
// = Acceptor oriented parallel to wall
(b) at impact with acceptor 2

Table 3a. Acceptor Accelerations
Measured and Predicted
36" Sand Wall
1 Mk82 Donor

ACCEPTOR ORIENT. (a)	<--COVER--> MAT'L (b)	T (in)	<---ACCELERATION (kg)---> <---CALCULATED---> 1D Model	2D Model	<TEST>
//(c)	None		4.1	0.25	2.5
//(d)	None		-51	-16	-6.5
+	None		1.81	1.5	1.0
+	800 HC	10	0.28	0.5	0.53
+	CBC	12	1		1.3

Table 3b. Acceptor Velocities
Measured and Predicted
36" Sand Wall
1 Mk82 Donor

ACCEPTOR ORIENT. (a)	<--COVER--> MAT'L (b)	T (in)	<-PEAK VELOCITIES (m/s)-> <---CALCULATED---> 1D Model	2D Model	<TEST>
//(c)	None		32	17.8	20
//(d)	None		18.8	10.2	10
+	None		17.1	16	10.6
+	800 HC	10	15.1	24.3	18.2
+	CBC	12	16.2		18

(a) // : Acceptor parallel to wall
+ : Acceptor perpendicular to wall
(b) 800 HC : 800 psi Aluminum Honeycomb
CBC : CEMCOM Inc, Type SA/CBC GC2
(c) Acceptor 1 response from wall impact
(d) Acceptor 1 response from impact with adjacent acceptor 2

Table 4. Acceptor Response
Measured and Predicted
8" Steel Grit Wall
2 Mk82 Donors

ACCEPTOR ORIENT. (a)	COVER MAT'L (b)	<-ACCELERATION(kg)-> CALCULATED 1D MODEL	TEST	<--VELOCITY(m/s)--> CALCULATED 1D Model	TEST
//(c)	CBC	3.8	6	54	38
//(d)	CBC	-86	-21	32	23
//(e)	CBC	89	12	46	38
+	None	27	33	37	56
+	800 HC	9	3.3	31	23.5
+	CBC	1.31	1.7	27	21.5

(a) // : Acceptor parallel to wall
+ : Acceptor perpendicular to wall
(b) 800 HC : 800 psi Aluminum Honeycomb
CBC : CEMCOM SA/CBC GC2 Chemically Bonded Ceramic
(c) Acceptor 1 response from wall impact
(d) Acceptor 1 response from impact with acceptor 2
(e) Acceptor 2 response from impact with acceptor 1

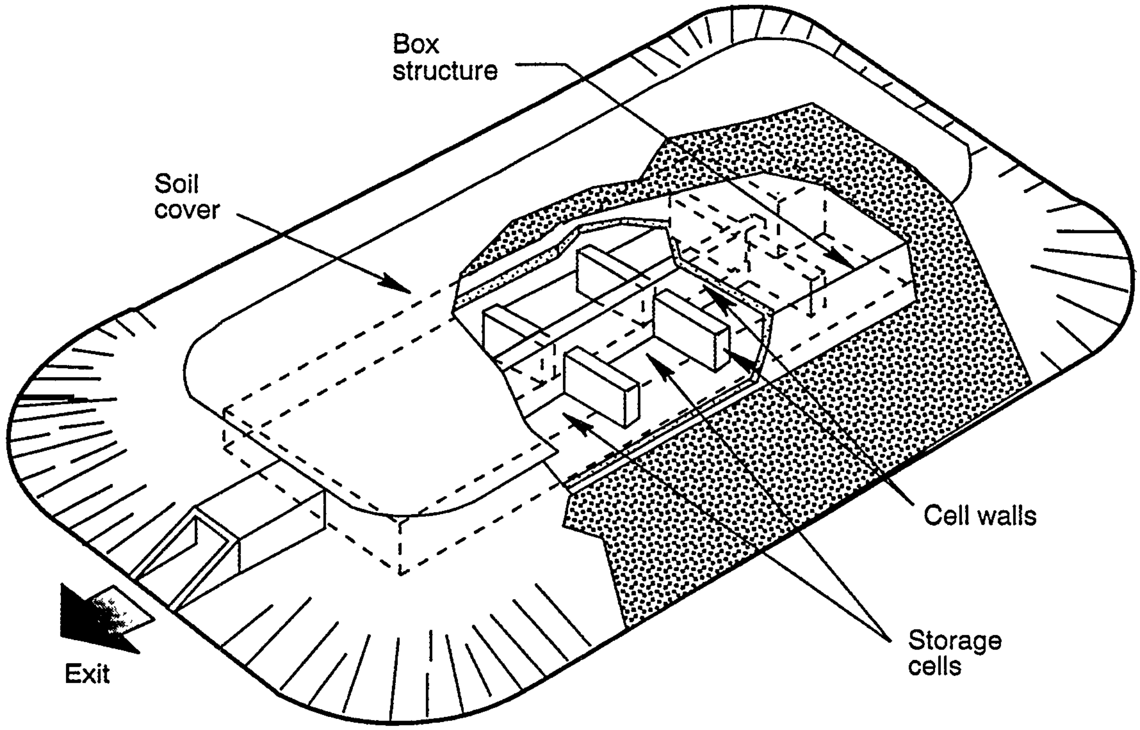

Figure 1. HP magazine concept.

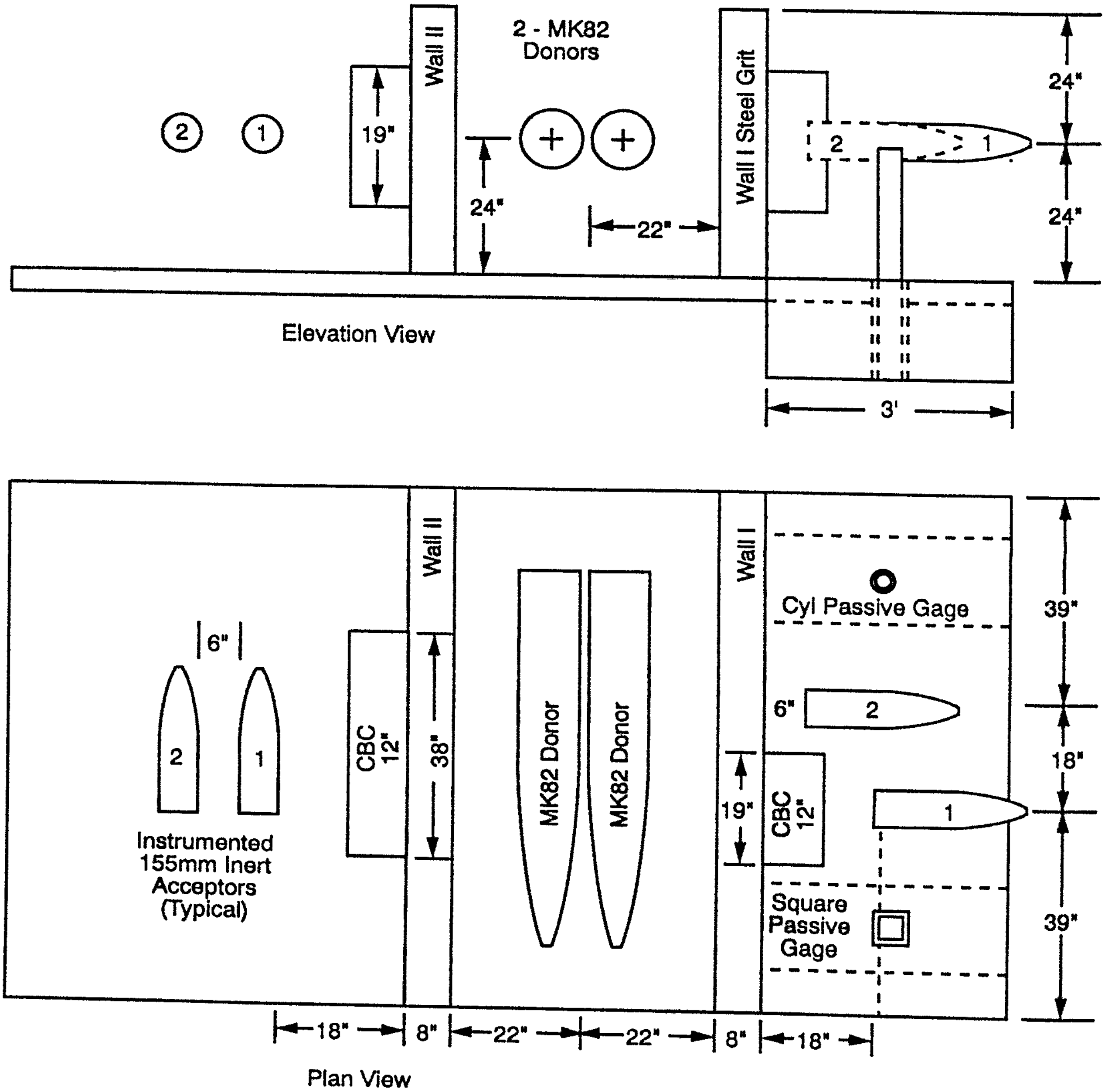

Figure 2. Typical small scale wall test setup.

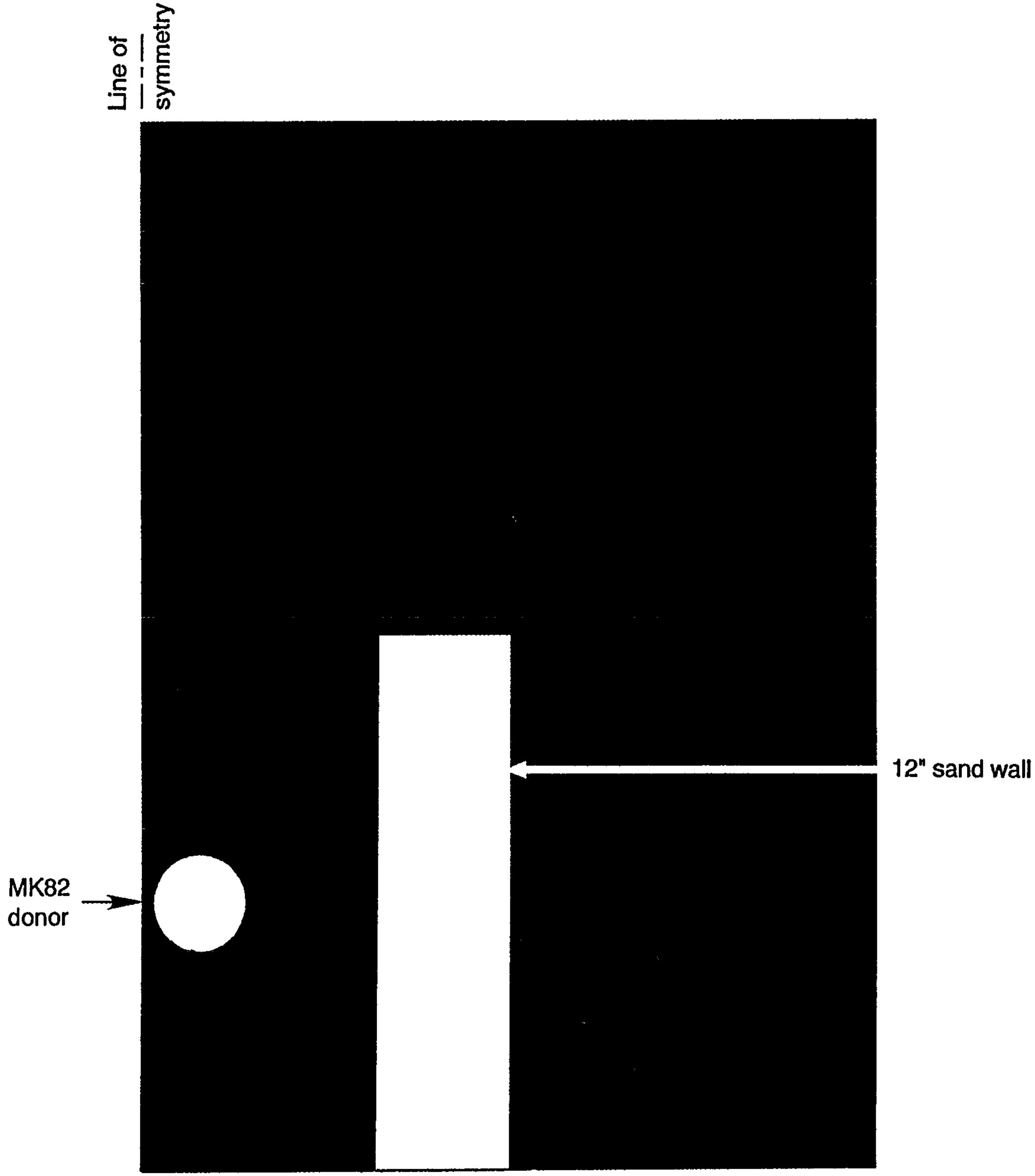

Figure 3. Two-dimensional AUTODYN model.

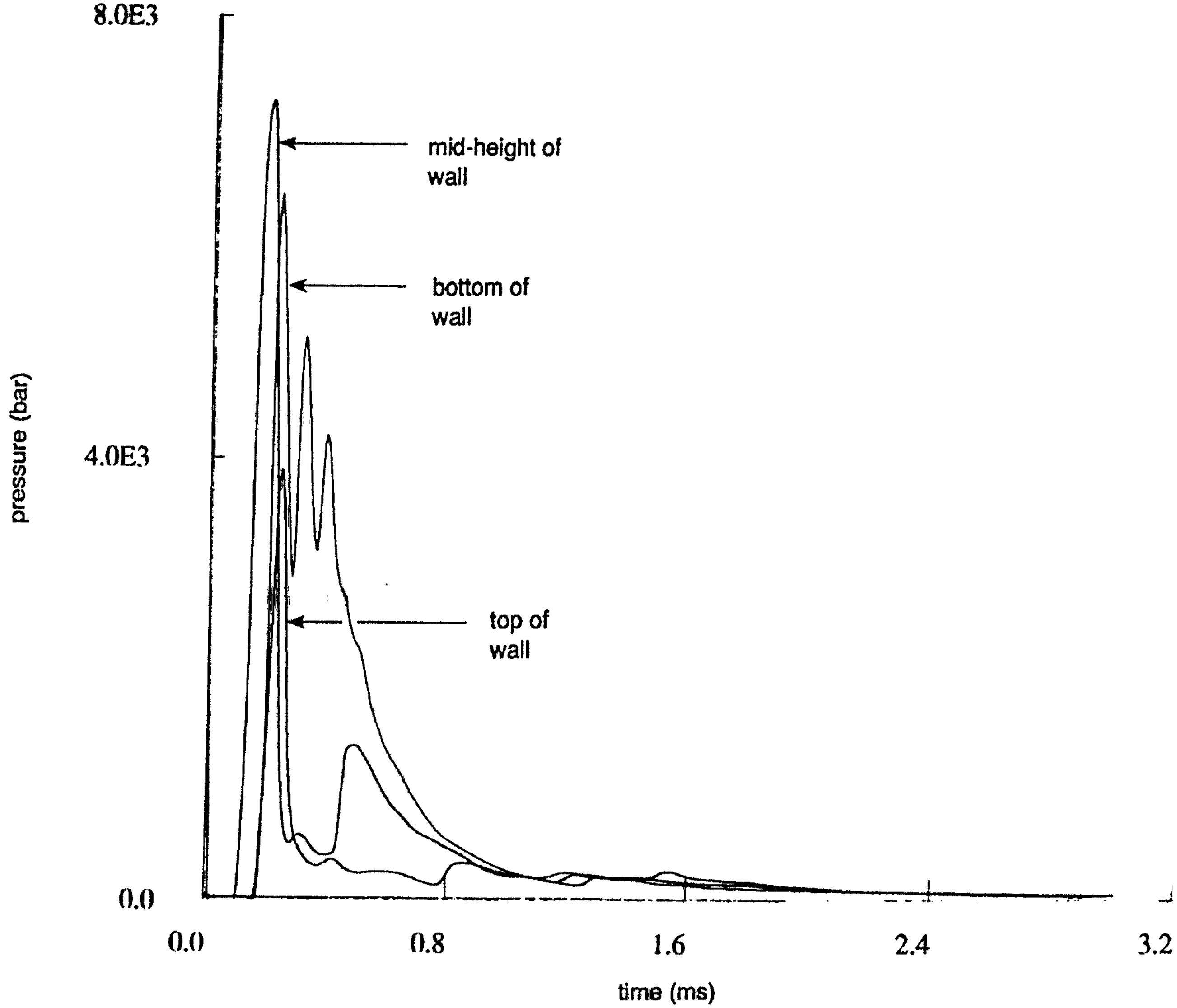

Figure 4. Pressure vs. time on donor side of wall.

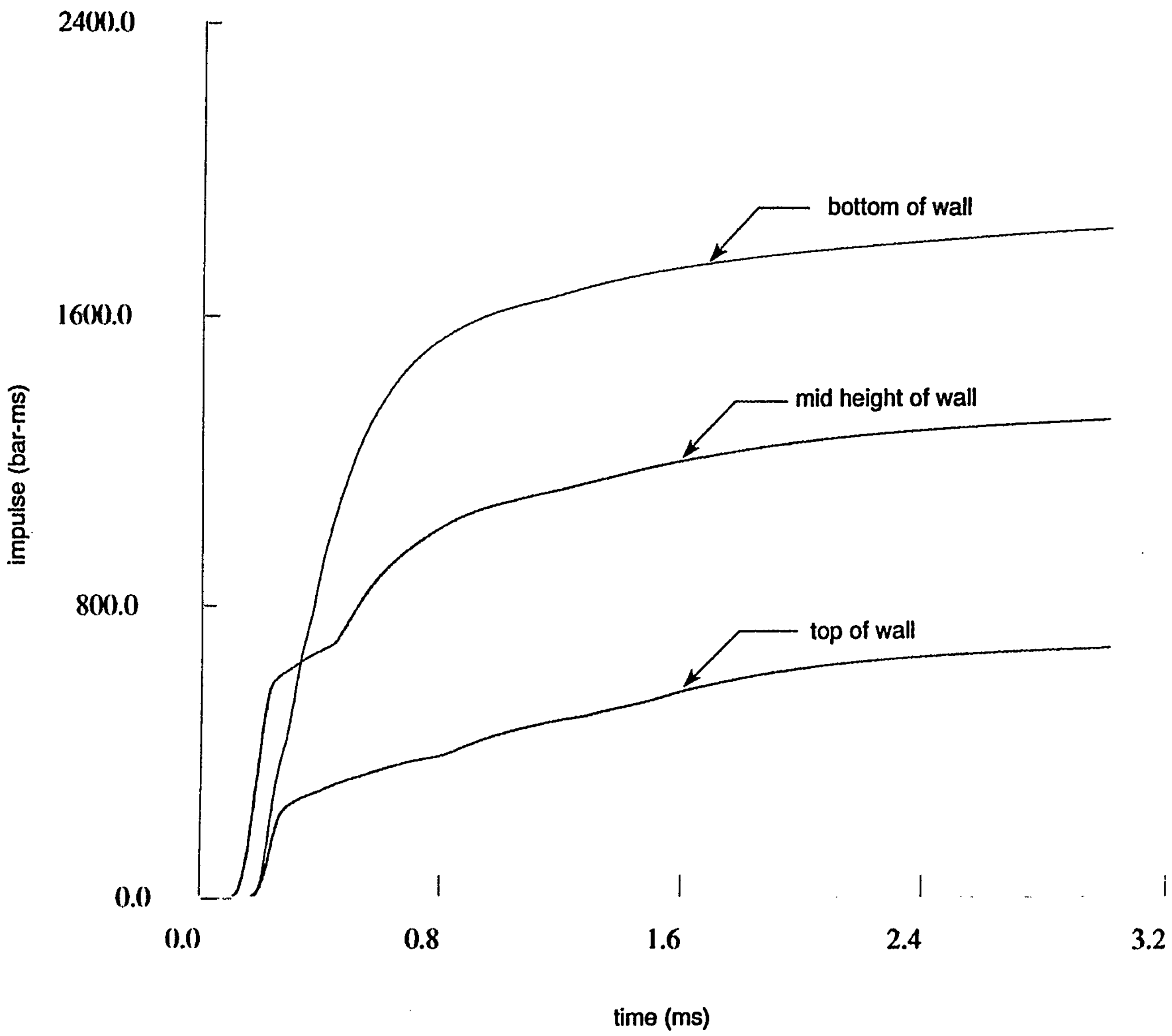

Figure 5. Impulse vs. time on donor side of wall.

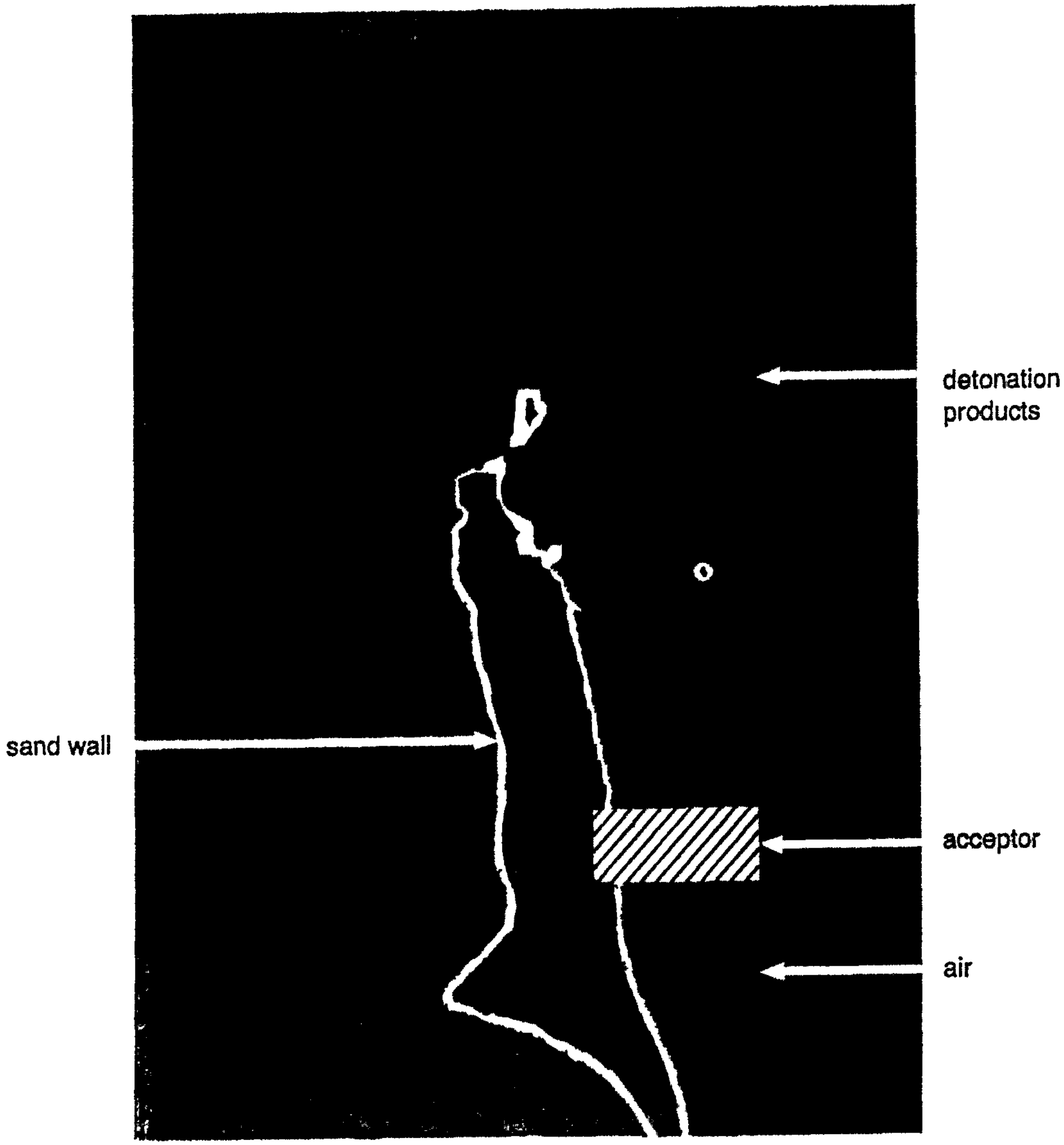

Figure 6. 12" sandwall response at T=1.59 ms.

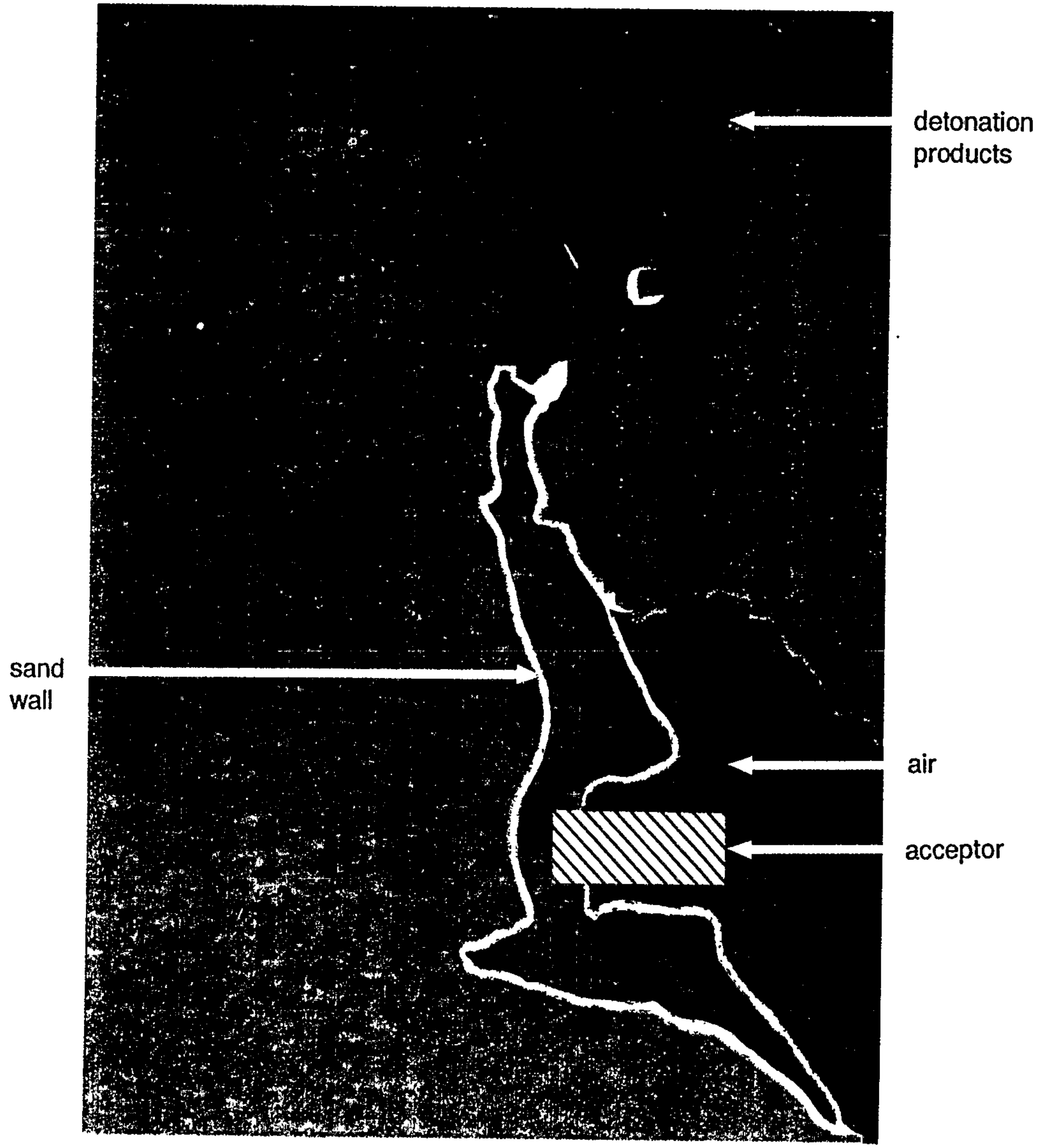

Figure 7. 12" sandwall response at T = 2.63 ms

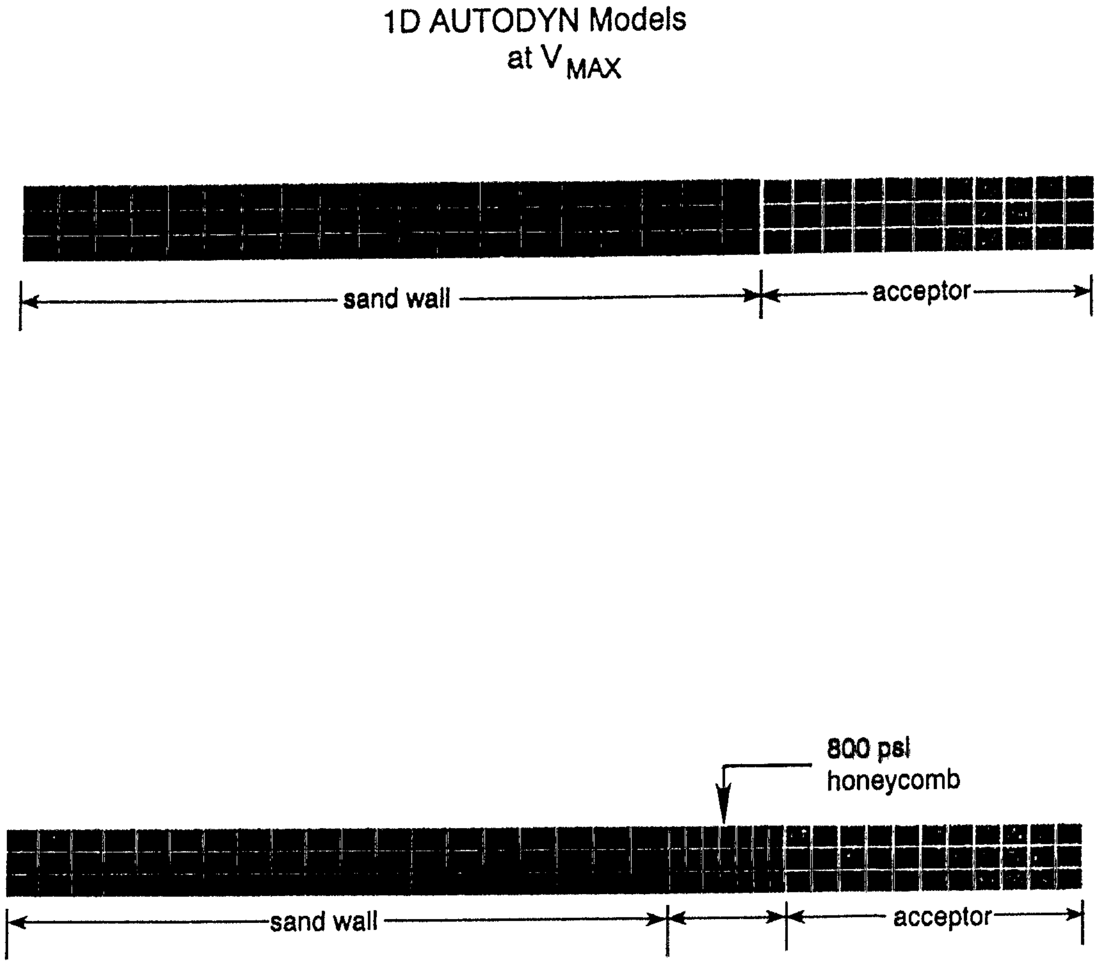

Figure 8. One-dimensional AUTODYN models.

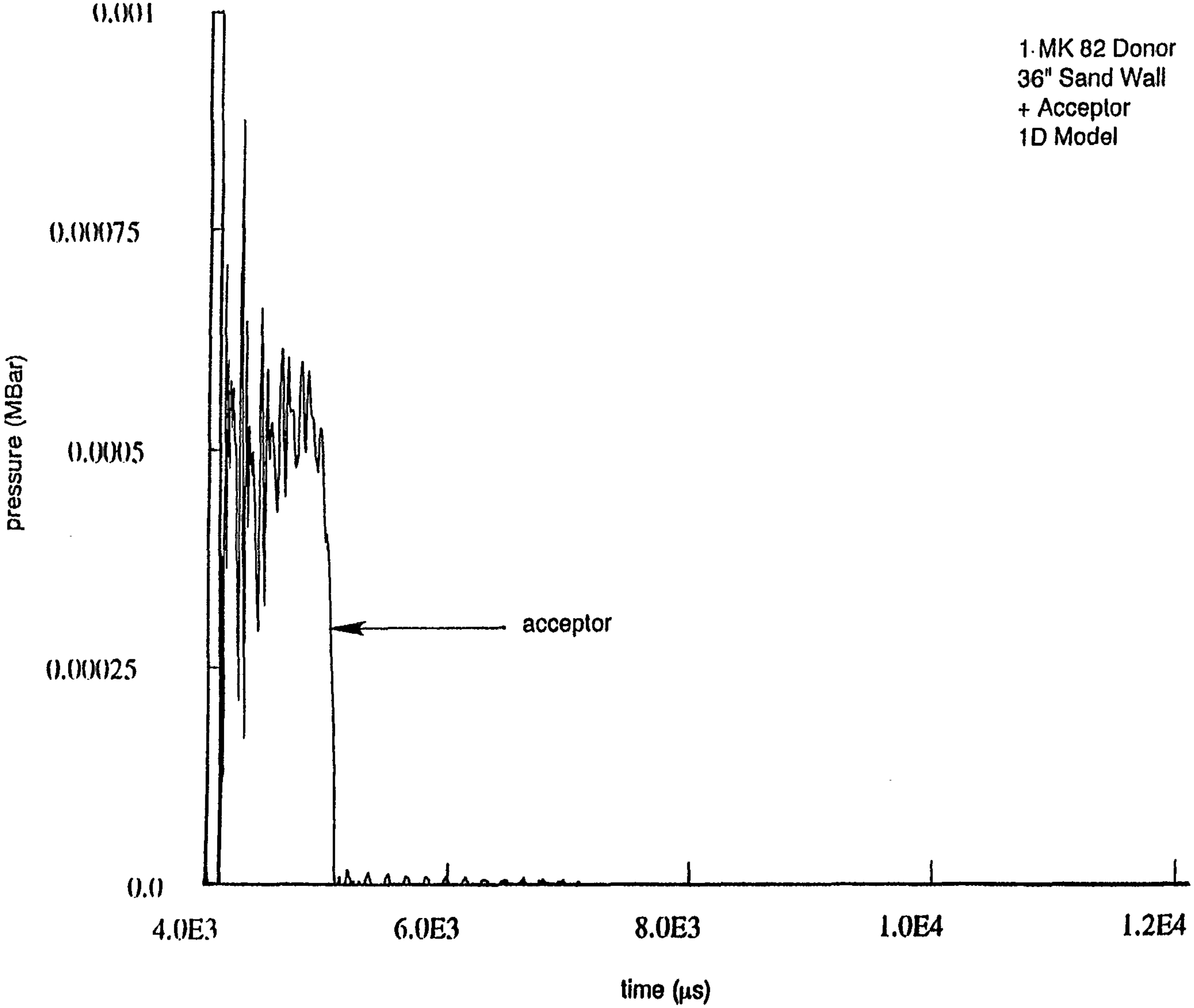

Figure 9. Pressure vs. time for acceptor opposite sand wall.

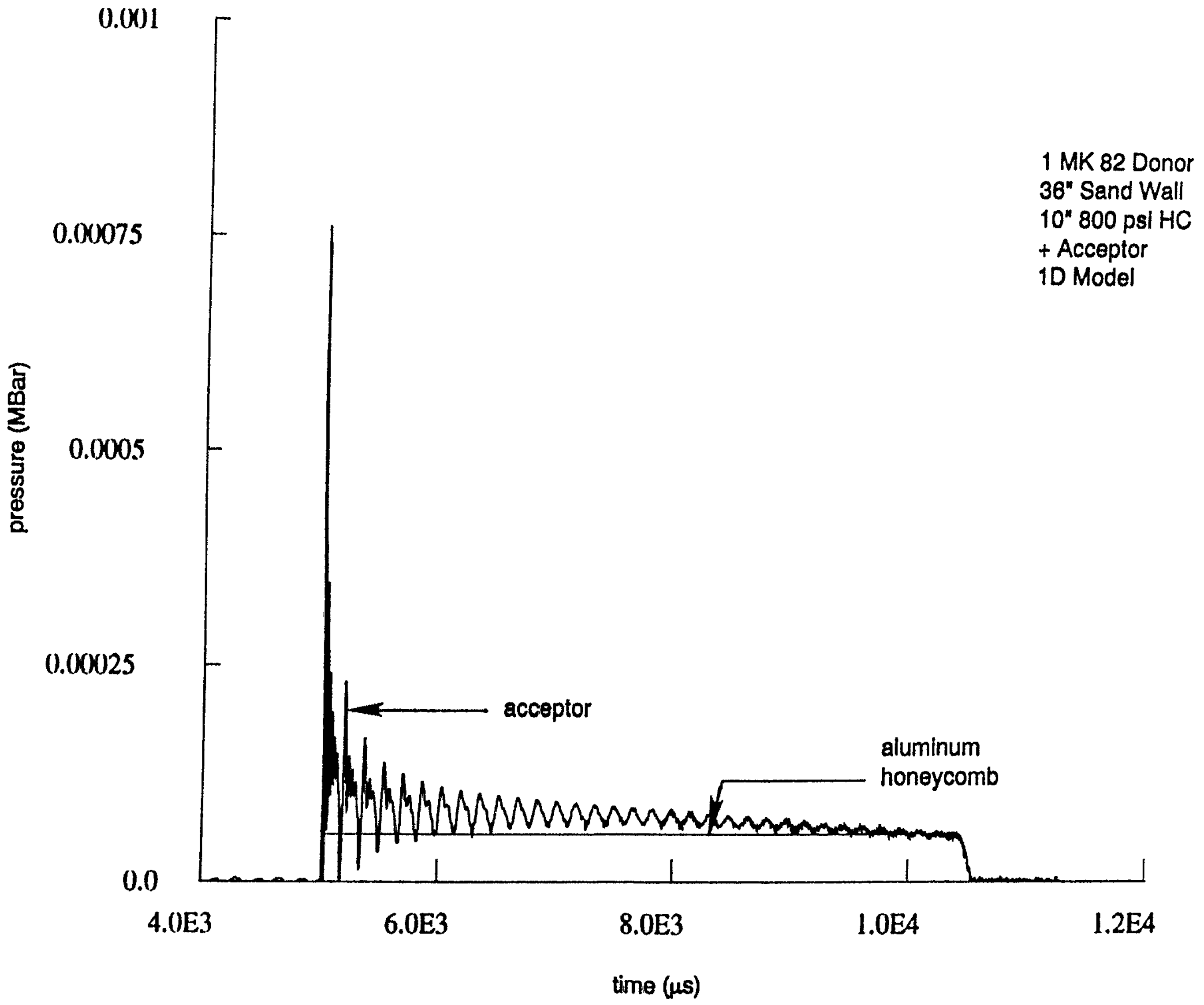

Figure 10. Pressure vs. time for acceptor opposite sand wall with 800 psi honeycomb cover.

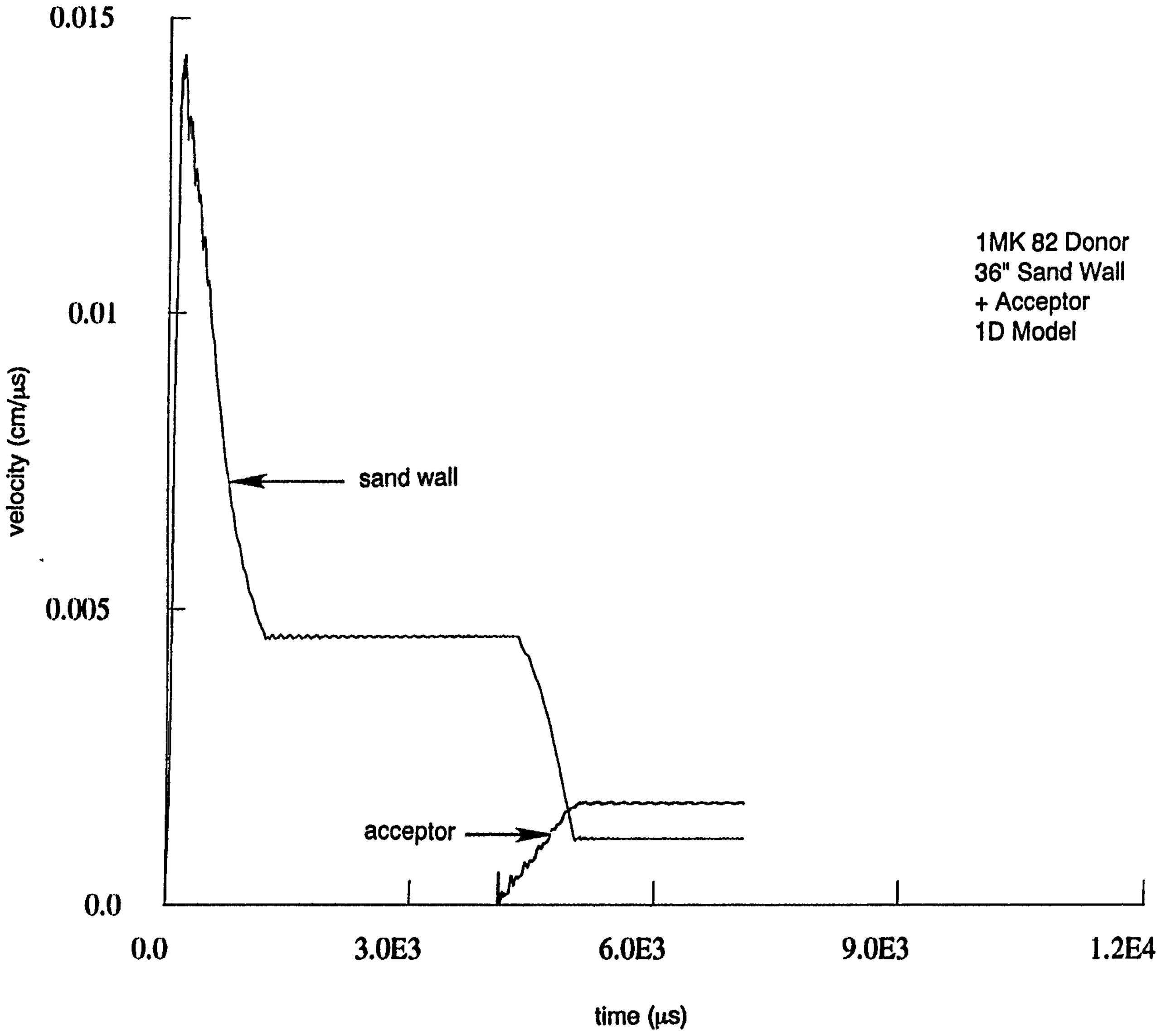

Figure 11. Velocity vs. time for sand wall and acceptor.

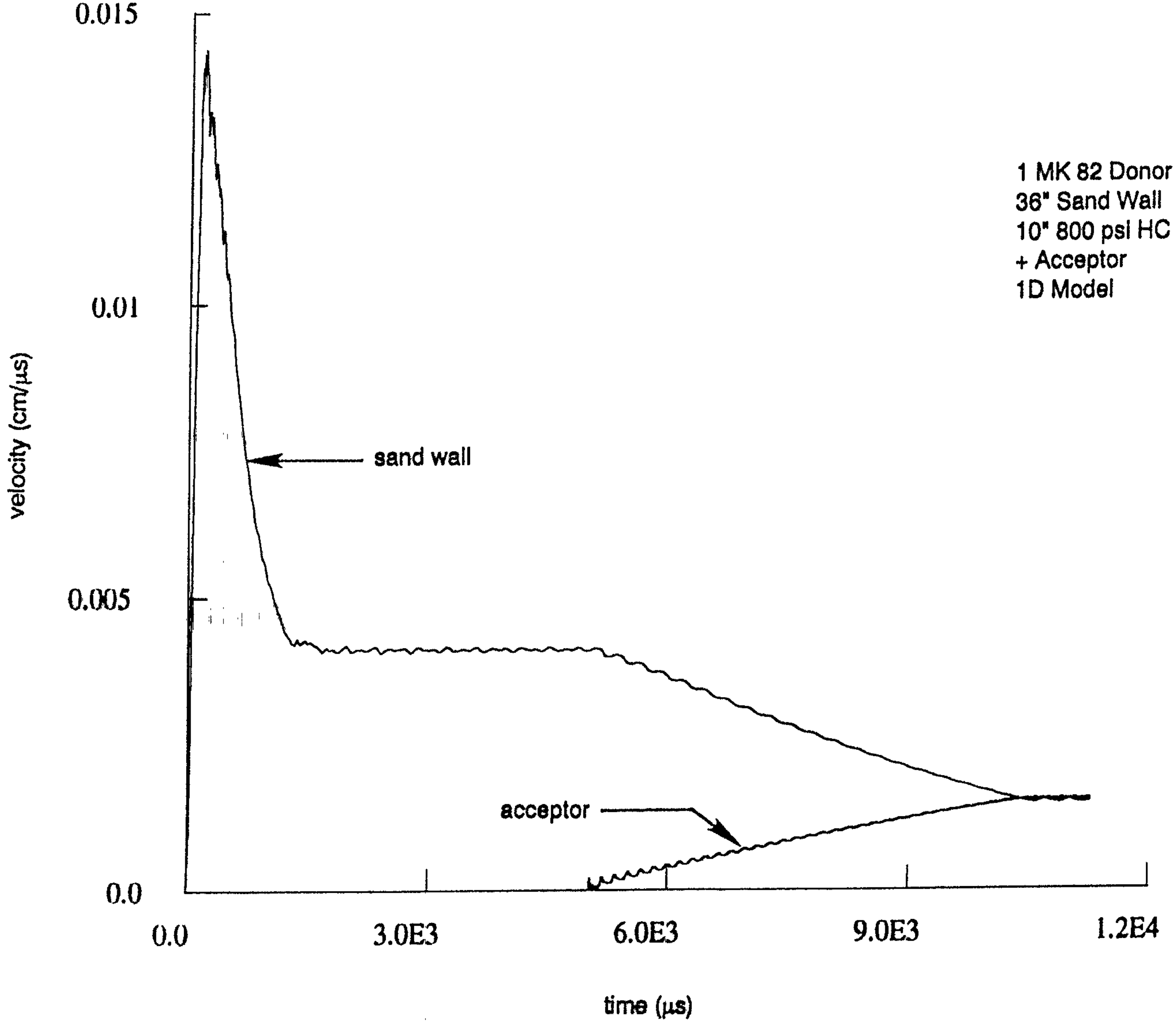

Figure 12. Velocity vs. time for sand wall (with 800 psi honeycomb cover) and acceptor.

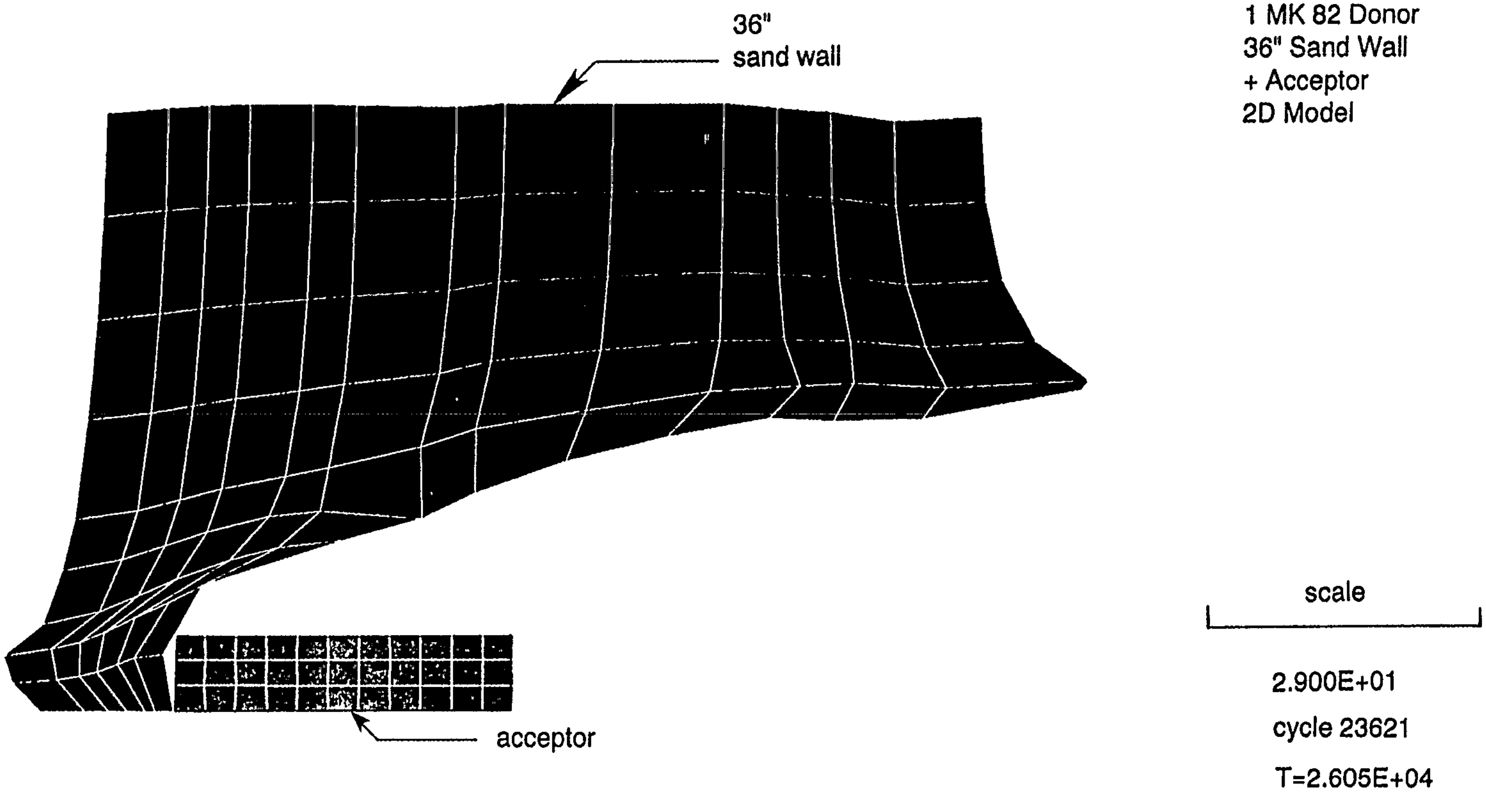

Figure 13. Two-dimensional model: sand wall and acceptor at 26 ms after impact.

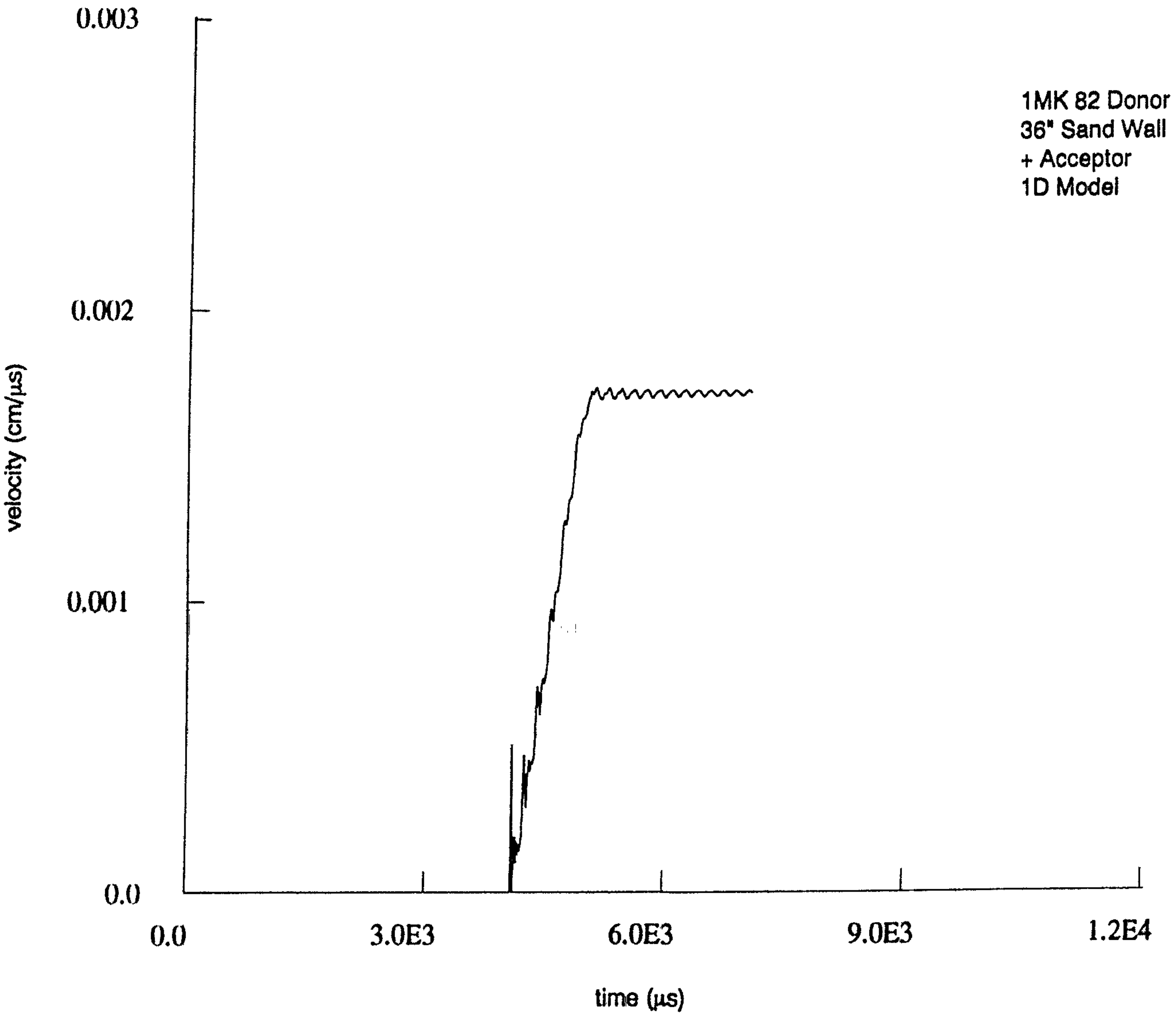

Figure 14. Acceptor velocity vs. time (sand wall - no cover).

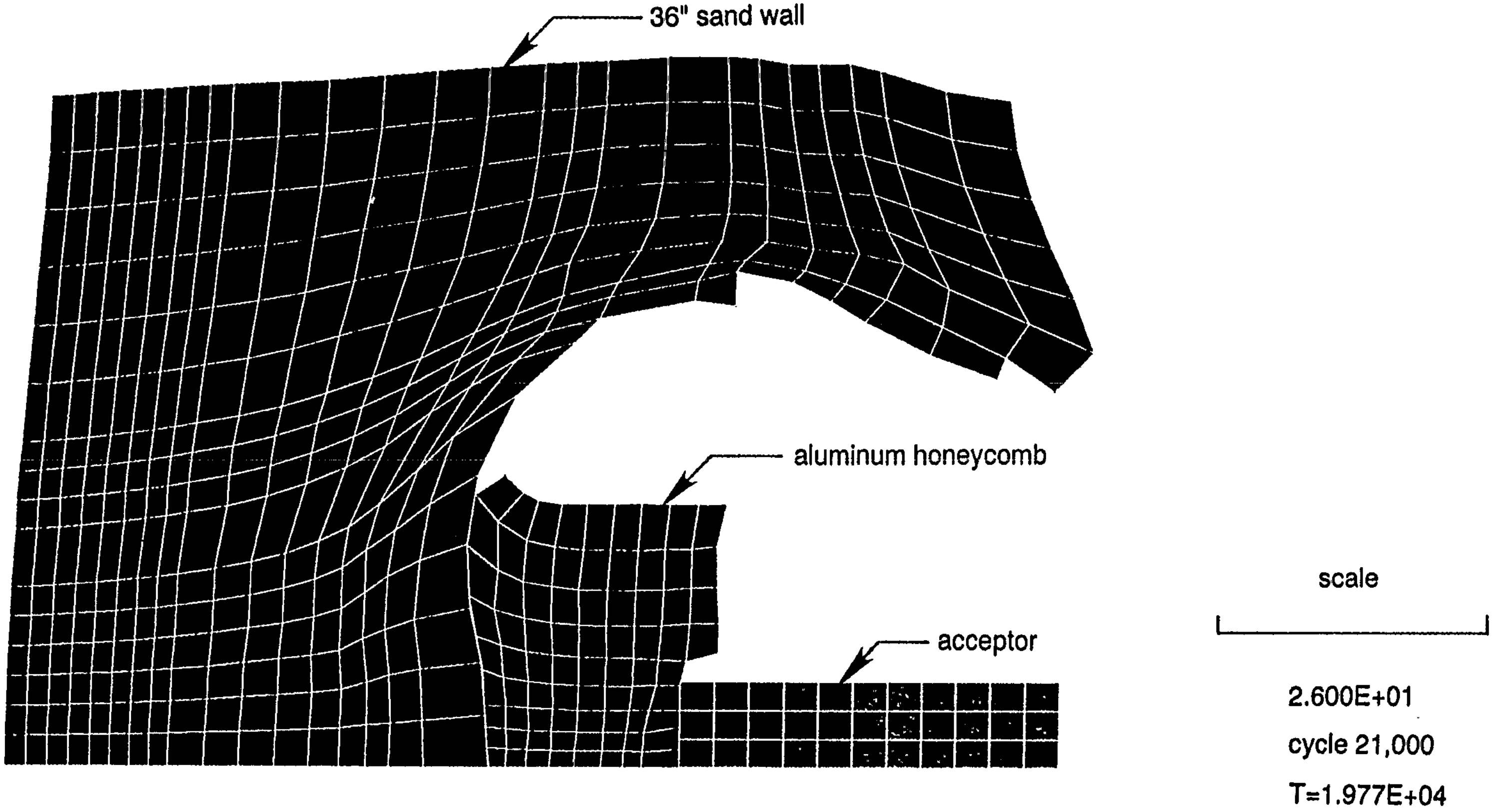

Figure 15. Two-dimensional model: sand wall, cover and acceptor at 19.8 ms after impact.

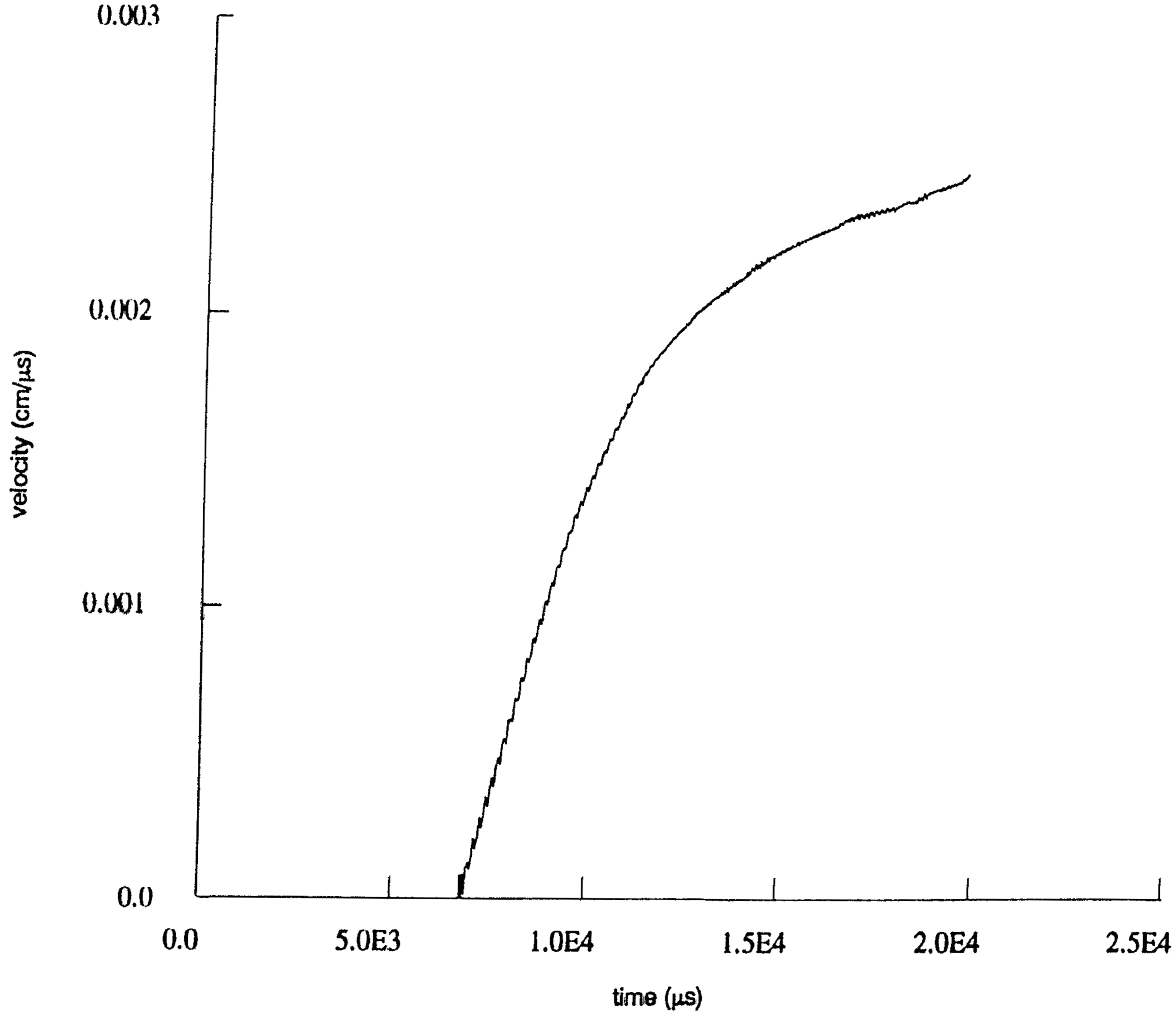

Figure 16. Acceptor velocity vs. time (sand wall with 800 psi honeycomb cover).

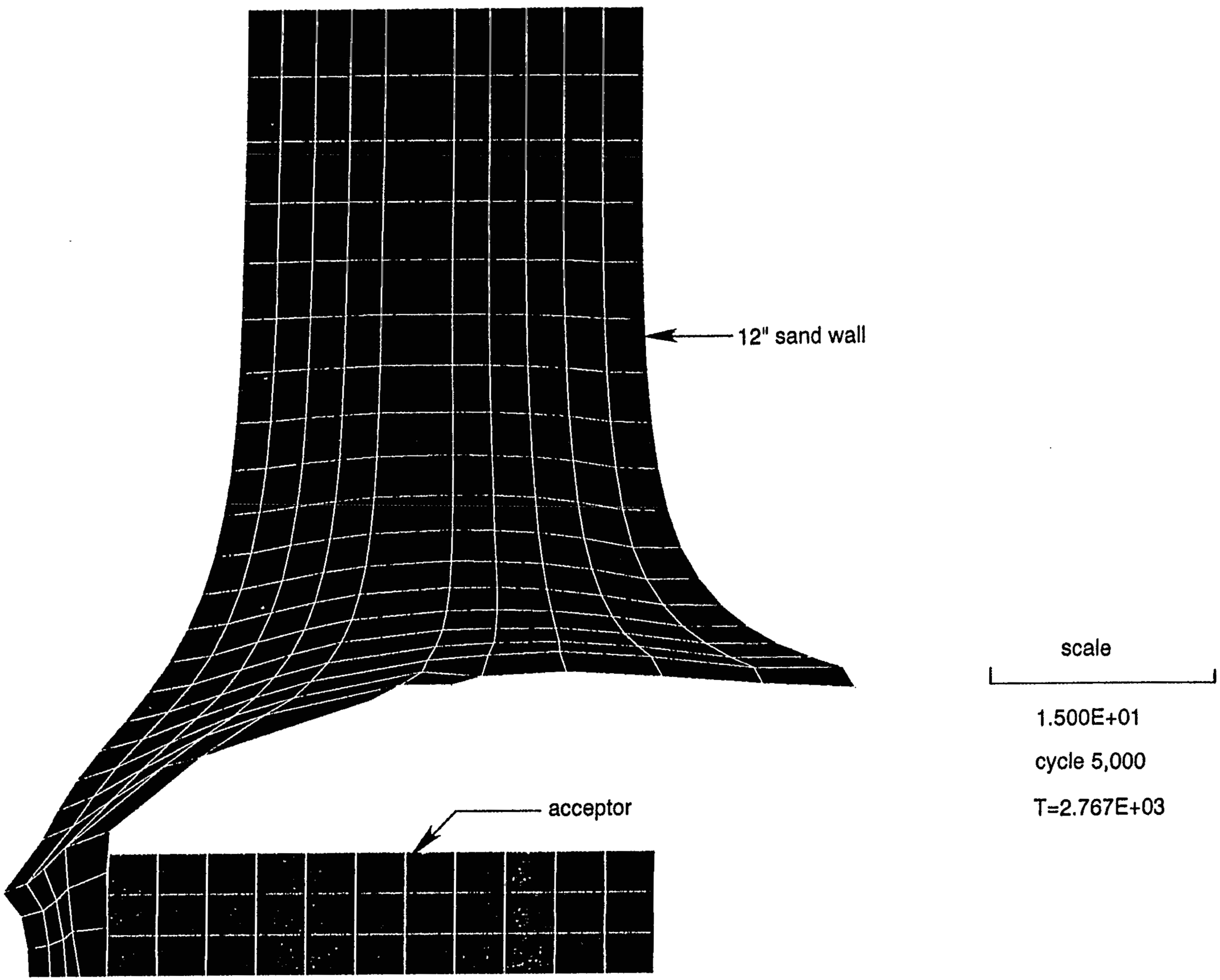

Figure 17. 12" sand wall and acceptor at 27.7 ms after impact.

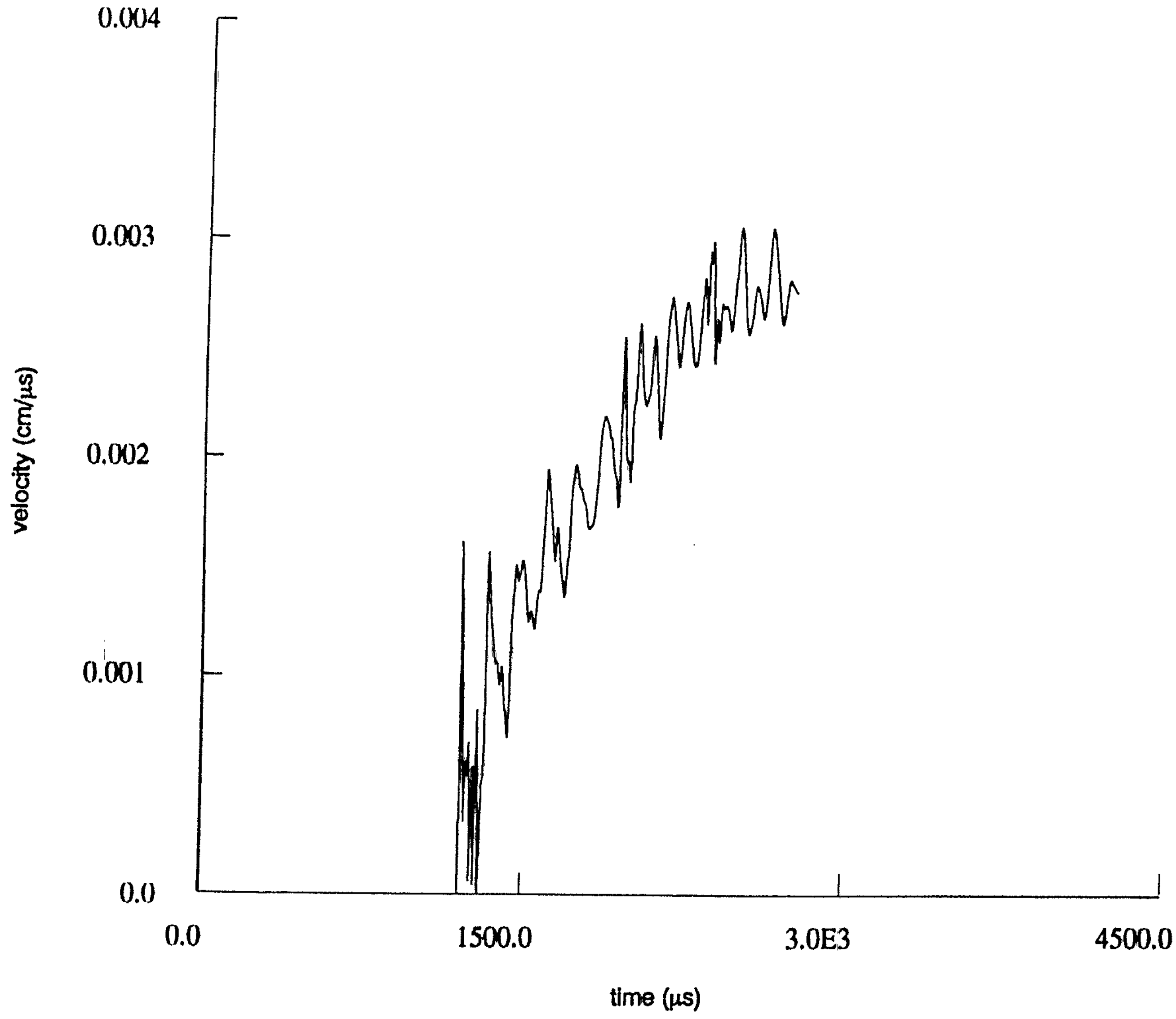

Figure 18. Acceptor velocity vs. time (12" sand wall - no cover).